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## HEAVY IONS IN JUPITER'S ENVIRONMENT

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### ABSTRACT

The extended atmosphere of the Jupiter system consists of heavy-element atoms and ions. This material originates on the satellite Io. Energy is lost from the thermal plasma in collisionally-excited optical and ultraviolet emission. The juxtaposition of Earth and spacecraft measurements provide insight concerning the underlying processes of particle transport and energy supply.

### INTRODUCTION

The formulation of planetary studies has been altered by the great expansion in the past decade of our detailed knowledge about other planets. When little was known, we relied on new capabilities to discover isolated facts: dominant constituents of surfaces and atmospheres, new satellites and rings, for example. Planetary phenomenology continues to surprise and to enrich, but emphasis increases on the identification and study of the physical principles underlying planetary processes. In this view, the other planets are the laboratory of earth science: nature varies the fundamental parameters - rotations, insulation, initial composition, etc. - and synoptic observations from Earth or spacecraft provide measurements for comparison with models. The goal is the governing physics of natural activity, both in remote planetary systems and in man's immediate environment.

Heavy elements dominate the composition and physical state of the jovian plasmasphere. This material originates in the interior of the volcanic satellite Io; it is injected into the surrounding space, transported by gravity when neutral and electrodynamics when ionized; it moves toward possible sinks in Jupiter's upper atmosphere, at rings and satellites, in interplanetary space. These atoms and ions are the extended atmosphere of Jupiter - an entity manifestly as complex as any large-scale geophysical system.

Jupiter's heavy-element extended atmosphere is a source of optical line emission, first sensed at ground-based observatories some eight years ago. It has been intensely studied in the intervening years both remotely and *in situ* by spacecraft experiments. Four distinct regimes can be identified. There is a "cloud" of neutral atoms moving away from Io along Keplerian orbits. A "hot" or "ultra-violet" complete torus of ions exists at Io's orbital distance from Jupiter. Closer to Jupiter, there is a region of "cool" plasma, the [SII] optical

emission nebula. These three components have been the object of complementary ground-based and spacecraft experiments, and are the focus of this paper. A fourth, less well-studied, lies outside the hot torus. It has diminishing density and optical activity, and it may consist partially of material escaping the jovian system into interplanetary space.

The synthesis of the many coupled phenomena into a single picture of Jupiter's environment demands that an interdisciplinary fabric be woven from the constituents of planetary science: geology, atmospheric and plasma physics, planetary magnetism. As such, this research object is an archetype for modern studies which emphasize formulating and observing planetary problems in terms of underlying physical processes.

This paper's purpose is to describe Jupiter's extended atmosphere as currently observed and understood (1980 June). An historical reference on the addressed topics is the book Jupiter [1], which contains summary Pioneer results and a review to 1976 of jovian optical line emission [2]. Two other major review books are in preparation: Physics of the Jovian Magnetosphere (A. Dessler, ed.) and The Satellites of Jupiter (D. Morrison, ed.). From the union of this material, a picture should emerge of an eminently observable planetary component, which will remain for years a rich resource to our field.

#### NEUTRAL ATOMS CLOUDS: IO AS A SOURCE OF HEAVY ELEMENTS

Jupiter's extended atmosphere was first detected in 1972 by Brown [3], who reported sodium D-line optical emission from Io. This free, neutral sodium is ejected into a cloud around that satellite [4], and resonant scattering of sunlight is the mechanism which renders the atoms visible [5]. Neutral potassium is similarly detected [6]. Collisionally-excited emissions from ionized sulfur and oxygen have been observed from Earth [7, 8], and by the Voyager plasma [9] and ultra-violet [10] experiments. The detection on Io of SO<sub>2</sub>, both gas [11] and frost [12, 13], implies a common origin at Io for all four heavy elements, which are the dominant constituents of Jupiter's environment.

The neutral alkali metals illuminate the movement of material away from Io, the first evolutionary stage of the jovian extended atmosphere. These atoms are visible due to the strong resonance transitions of the valence electron; they are essentially invisible when ionized. Sulfur and oxygen play a complementary role; their ions, classical light sources in astrophysical nebulae, manifest the second evolutionary stage: residence in the ionized plasma which corotates with Jupiter. Light from the neutral atoms is analyzed for characteristics of the plasma source; the ions permit physical observations of the plasma itself.

The mechanisms have not been established by which specific elements are selected and injected from Io into circum-jovian space. It is reasonable to suppose a relationship to other unusual phenomena, such as Io's modulation of jovian decametric radiation [14]; the emission of non-thermal radiation from Io at centimeter wavelengths [15]; and Io's internal heating [16] which causes volcanic differentiation and eruption [17, 18]. The geometry of the volcanic plumes implies ballistic velocities smaller than is required to escape Io's gravity ( $\sim 2.5 \text{ km s}^{-1}$ ) [19] and to account for the residual velocities characteristic of the Io-connected neutral cloud ( $< 4 \text{ km s}^{-1}$ ) [20]. Sputtering by ion-impact at the surface [21] or at the top of the atmosphere [22] can supply neutral atoms with sufficient speed, and this process seems to be the best candidate for dividing the non-volatile, alkali metals to the atomic scale. An Io atmosphere poses difficulties for sputtering [2], most recently the unobserved [23] but expected modulation of the neutral-atom clouds due to the changing orientation of the convected ion flux (corotation-fixed) with respect to the highly asymmetrical, distribution of a volatile gas such as SO<sub>2</sub>, (solar-fixed) [24].

The magnitude of the Io sodium source and the lifetime against ionization can be estimated by modelling the brightness and morphology of the neutral sodium cloud. The Harvard studies [23, 20] indicate a lifetime of about 20 hours at the cloud periphery. Since the photoionization lifetime is much longer, electron impact is generally assumed to be the governing ionization process [25]. When combined with a sodium inventory not including the immediate Io vicinity, this time constant implies an injection rate of  $2 \times 10^{25}$  sodium atoms  $s^{-1}$  [20]. There are at least two deficiencies in this estimated sodium source. First, it does not include atoms at large distances from Io on higher-velocity or longer-period orbits originating at Io [26]. This selection effect could result in a factor 3 undercount. Second, sodium is lost in transit through the hot torus in which Io is embedded, where the electron impact ionization lifetime is about 1 hour [27]. Estimating an average 2 to 3 hour transit time in this region, the required Io sodium source is raised by an order of magnitude. A modified estimate of the sodium source is  $6 \times 10^{26}$  sodium atoms  $s^{-1}$  or  $2 \times 10^9$  sodium atoms  $cm^{-2} s^{-1}$  averaged over Io's surface.

The total Io atomic source can be computed from an estimate of the fractional abundance of sodium. This information is present in the Voyager charged particle experiments, but one must assess processes which may differentially partition ion species, both in space and energy. The spatial distribution of neutrals is isomorphic to the associated ion source, and it is strongly affected by the species-dependent lifetime against ionization [28]. Also, entirely different production mechanisms may apply to the volatiles and alkali metals [29]. If the sources of different ions are not coincident, species-independent diffusion would be required to uniformly mix the plasma. The uncertainty about such processes notwithstanding, a sodium mixing ratio of 1% to 10% is indicated both inside and outside Io's orbit by the Voyager plasma experiment [30], and that value appears consistent with the LECP higher-energy observations near the magnetopause [31]. Assuming this ratio also applies to the Io source, the required total ejection flux at Io is  $10^{28 \pm 7}$  atoms  $s^{-1}$ .

The short- and long-term stability of Io's neutral sodium cloud is surprising and unexplained. Because the hot torus at Io's orbital distance is confined near the centrifugal symmetry surface [32, 33, 34], which is fixed in System III longitude and inclined at about  $7^\circ$  with respect to the satellite orbital plane, one expects a  $\lambda_{III}$ -modulation of the cloud (6.6 h period) caused by varying either production at Io or loss by ionization. The observed bulk effect is slight [35, 23]. Also, ultraviolet indicators of plasma conditions near Io changed drastically between 1973 (Pioneer [36]) and 1979 (Voyager [10]), but little change has been noted in the sodium cloud over that period [37, 38].

#### THE JOVIAN HEAVY-ION PLASMA

The Cool Plasma. The first detection of heavy ions near Jupiter was the discovery in 1975 of forbidden optical line emission from  $S^+$  [7]. This phenomenon has been intensely observed from Earth with a variety of techniques, including (1) imaging, which investigates morphology; (2) high-resolution spectroscopy, which studies kinematics; (3) spectrophotometry, which measures abundance and ambient plasma conditions.  $S^+$  was also recorded by the Voyager I plasma experiment in the optical emission region (the cool plasma), providing complementary information.

One- and two-dimensional images [39, 34] confirm and extend conclusions from brightness variations [40, 41, 33] that the [SII] emission forms a variable partial torus between about 4.7 and 5.7  $R_J$  from Jupiter, lying near the magnetic equator or the centrifugal symmetry surface, which are inclined with respect to the (coincident) rotational equator and orbital plane. Reports by the Israeli group of an emission void spatially associated with Io [7, 42, 43] have not been

confirmed by other observers. The total radiated power from this cool plasma region is about  $10^{10}$  W.

The convective and thermal motions of the  $S^+$  ions have been studied by measuring the radial velocity and Doppler line width of the [SII] optical emission [33]. The ions accurately corotate with Jupiter, and the ions have kinetic temperature variable between about 15,000 and 40,000 K. Over most of that range of electron temperatures, sulfur ionization equilibrium calculations predict  $S^+$  to be the dominant charge state of sulfur [44].

The internal structure of the  $S^+$  ion provides an important capability to measure charge density in the jovian plasma from ground-based observatories [45]. The first two excited levels of that ion,  $^2D_{5/2}$  (1.846 eV) and  $^2D_{3/2}$  (1.842 eV) are connected to the groundstate,  $^4S_{3/2}$ , only by electric quadrupole and magnetic dipole matrix elements, since the transitions require a change of spin. The upper levels are populated only as the result of electron collisions, not photon absorption; the slow decay by photon emission proceeds with lifetimes  $2 \times 10^3$  s (6716Å) and  $6 \times 10^2$  s (6731Å) for  $^2D_{5/2}$  and  $^2D_{3/2}$ , respectively. Consider the behavior of the  $S^+$  ion immersed in a bath of thermal electrons sufficiently energetic to induce upward transitions from the groundstate, filling the excited levels in proportion to their multiplicities, 6 and 4, (difference in Boltzmann factor ignored). In the limit of lowest electron density, all excited ions will photon decay, and the intensity ratio equals the excitation ratio:  $I(6716\text{\AA})/I(6731\text{\AA}) = 1.5$ . In the limit of high electron density, collisional de-excitation and the shorter lifetime of the  $^2D_{3/2}$  level becomes important: the photon intensity is then the ratio of the equilibrium populations divided by the respective lifetimes, or 0.4. The transition from one asymptotic ratio to the other occurs when the time between electron collisions approximates the decay time. For plasma temperatures at which  $S^+$  is the dominant equilibrium constituent, the cross-over occurs for  $10^2 < [n] < 10^4 \text{ cm}^{-3}$ , in which range the ratio  $I(6716\text{\AA})/I(6731\text{\AA})$  is a sensitive electron density indicator.

Ground-based observation of the [SII] region have found the ratio  $I(6716\text{\AA})/I(6731\text{\AA})$  predominantly in the high-electron density regime; that is, implying  $[n] > 10^3 \text{ cm}^{-3}$  [46, 40, 33, 41, 34]. These high densities have not been reconciled with 1973 Pioneer in situ findings [47], but they are consistent with Voyager I results [9, 48].

Voyager found a narrow peak of  $S^+$  density about  $5.3 R_J$  from Jupiter [49]; the ion temperature and electron density were in the range measured in the [SII] emission. The evidence is compelling that this plasma feature corresponded to the [SII] optical emission region at the epoch of Voyager I. Detailed, numerical comparisons of Voyager and groundbased results are frustrated by the demonstrated short-term variability of the [SII] emission [39]. Nevertheless, the connection between the two data sets has established the plasma-diagnostic [SII] emission as a powerful tool to study one component of the jovian plasma on a continuing basis from Earth.

**The Hot Torus.** A complete and nearly uniform torus of ultraviolet emission from higher ionization states of oxygen and sulfur was observed by the Voyager UVS experiment [10]. The radius of this "hot" torus is the same as Io's orbit ( $5.9 R_J$ ), and the cross-sectional radius is about  $1 R_J$ . It lies near the magnetic equator and the centrifugal symmetry surface. The dominant spectral features, at about 685Å and about 833Å, are assigned to unresolved blends of  $S^{++}$  and  $S^{3+}$  prompt emission stimulated by electron collisions. Weaker lines of  $S^{++}$  and  $S^{3+}$  occur at 1018Å, 1070Å and 1198Å; a feature at 900Å has not been assigned [50]. IUE satellite observations [60] have identified hot torus emissions of  $S^+$  (1257Å),  $S^{++}$  (1199Å) and  $O^{++}$  (1664Å); a spectral feature near 1729Å is unidentified. The total UV radiated power is about  $2 \times 10^{12}$  W.

Major instrumental and theoretical impediments block a unique inversion of the Voyager UVS observations in terms of the composition and physical state of the hot torus. The spectrograph did not have adequate resolution to separate the blended lines of different multiplets, so that relative species contributions must be modelled by exterior assumptions. The atomic constants which govern the processes of ionization, recombination, excitation and radiation are not well determined, having predominantly a theoretical rather than experiment basis. (In fact, the Jupiter extended atmosphere may prove to be a continuing source of fundamental atomic data: it has already corrected the energy levels of S<sup>+</sup> [33]).

Despite their limitations, the UV measurements provide an overall view of the hot torus which is consistent with the thermal and compositional picture from the Voyager plasma experiment and ground-based studies. Assuming a single Maxwellian electron distribution characterized by a temperature of  $10^5$  K, the identified UV emissions can be self-consistently explained by a charge-neutral plasma dominated by sulfur and oxygen ions with a few thousand charges per cm<sup>-3</sup> [10, 51]. With recalculated excitation coefficients, Strobel and Davis [52] produce the observed emission with a lower electron temperature ( $5 \times 10^4$  K), but they require a second, hotter electron component to achieve the higher ionization states. A two-component electron distribution is also reported from the Voyager plasma experiment [53]. Ground-based observers have measured collisionally-excited emission from S<sup>+</sup> in the hot torus at 9532 Å [54]. The intensity is consistent with the equilibrium calculations of Shemansky [51], and the ion kinetic temperature is about  $3 \times 10^5$  K, consistent with Voyager plasma results in this region [49].

#### UNDERLYING PROCESSES

The antecedent sections characterize a complex system in dynamical balance having deceptively static physical properties. Not only do these phenomena evolve on all accessible time scales, but they embody an inexorable flow of material and energy from source to sink. The physical processes underlying those flows are subjects of controversy, the more exciting for being the very underpinnings of this extended atmosphere.

Transport. Only two aspects of material transport in Jupiter's extended atmosphere has been seen directly: the movement of alkali metal atoms away from Io and the spatial distribution of the thermal plasma dominated by sulfur and oxygen. The production of atoms and ions off, up and away from Io is not observed, neither is the denouement: the processes by which these ions leave the plasma. Leaving aside the possibility of enlightenment by discovery, the most tractable link in this chain is probably the diffusion process by which the ions are redistributed from their source(s) into an equilibrium spatial profile.

The most recent efforts on this topic are attempts to match Voyager results using models in which the ion source is localized at Io. Froidevaux [55] finds that the profile outside Io's orbit can be understood with a steady state model using centrifugally-driven flux tube interchange, without requiring interchange driven by neutral winds in Jupiter's ionosphere. Richardson *et al.* [56] find that a time-dependent model and a discontinuity in the diffusion process at Io's orbit are required to match the entire plasma profile. They hypothesize that a major ion-injection event took place 1 to 100 days prior to Voyager 1 encounter, which is difficult to reconcile the stability of the UV torus over that period [10].

The assumption of both diffusion models that the ion source is localized at Io must be questioned on both logical and observational grounds. If it is demonstrated that sulfur and oxygen are distributed widely in neutral clouds (analogously to the alkali metals), then entirely different initial conditions for

the modelling are required. Shemansky [57] presents evidence that copious ionization is not taking place in the immediate vicinity of Io based on the absence of associated UV emissions. It can be anticipated that a radially-distributed ion source could be matched to the observed ion profile with a time-independent diffusion model.

The Energy Budget. The clearest energy demand with regard to the extended atmosphere is to supply the  $2 \times 10^{12}$  W drained by the UV emissions from the electron population in the hot torus. In 1978 Brown [58] suggested that the equilibration of newly created ions from the alkali metal neutral clouds could supply the power drained from the cool plasma by the [SII] emissions. That idea can be reframed for the much greater power requirement of the hot torus by assuming that sulfur and oxygen are distributed in neutral clouds. It is crucial to this argument that the atoms are ionized experiencing the full jovian magnetic field.

The newly-created ion appears to be very energetic in the rest-frame of the corotating plasma: its gyration velocity is the local speed of corotation minus the Keplerian velocity of the neutral cloud. For an atom with Io's orbit, this relative speed is  $57 \text{ km s}^{-1}$  or 17 eV per nucleon, 540 eV or  $4.2 \times 10^6$  K for a sulfur ion. The equilibration to  $3 \times 10^5$  K [49, 54] proceeds through Coulomb collisions with background ions. This process is speeded by further ionizations and will be accomplished in 10-20 days [59]. To deliver  $2 \times 10^{12}$  W to the plasma ions would require  $2 \times 10^{28}$  ionizations per second. The different masses of the heavy ions can be ignored for these purposes, and it is seen from the work in the first section that studies of the neutral clouds and the observed sodium ion mixing ratio predict a source of this magnitude.

It remains to connect the energy delivered to the  $3 \times 10^5$  K ions to the  $5 \times 10^4$  K electrons which excite the forbidden lines. It is helpful to adopt a microscopic view. The total hot torus volume is estimated at  $4.3 \times 10^{31}$  cm<sup>3</sup>, and  $2 \times 10^{12}$  W translates to  $0.3 \text{ eV cm}^{-3} \text{ s}^{-1}$ . The energy density of the ion component of the plasma ( $10^3 \text{ cm}^{-3}$ ) is  $U = 4 \times 10^4 \text{ eV cm}^{-3}$ . Whatever else happens, the heavy ions will transfer energy to the electrons through Coulomb collisions with time constant  $T = 3 \times 10^5$  s [59], which constitutes a power  $U/T = 0.1 \text{ eV cm}^{-3} \text{ s}^{-1}$ , similar to the demand of the collisionally-excited emissions. All the Coulomb equilibrations are faster than the 25-day residence time predicted for the plasma by dividing the total number of ions by the neutral supply rate.

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